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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: R.P.D.53

PROPELLANT FEED VALVES FOR STARTING AND CONTROL OF ROCKET MOTORS

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SUMMARY

The type of valve described in this note has been designed to use the pressure in the feed system between the valve and the injector as the controlling medium. This allows automatic control of the valve and safe starting and operation of the rocket motor to be obtained with greater simplicity than in other types of valve hitherto known which are intended to fulfil the same purpose; the new valves also permit the use of a timing sequence for propellant control to be dispensed with.

The principle of operation and the types already developed are described in full, with suggestions for further applications. The method used for calculating the valve dimensions is given in an appendix.

1. Valves

I Schoenheit, W

II Title

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1 Introduction

Experience has shown that rocket motors of over 2,000 to 3,000 lb thrust can be started more safely by using a reduced rate of flow for the initial injection of the propellants, and propellant feed valves have been designed which allow the pressure of fuel and oxidant at the injector to develop gradually. When, however, the valves start to open the passages between the valves and the injector have to be filled before injection into the combustion chamber takes place. At the instant injection starts the pressure in the system downstream from the valve is only the differential pressure caused by flow through the injector nozzles, but after ignition the pressure downstream from the valve is immediately increased to this pressure plus the pressure in the combustion chamber. It is essential that at this instant the moving part of the valve has reached a position in which the starting flow rate is delivered; the valve has then to move to the completely open position to deliver the full flow of propellant. It is difficult to make the valve move through the successive stages of opening described above by causing it to follow a prescribed timing sequence and attempts were made to overcome this difficulty by using a different type of valve and employing the pressure downstream from the feed valve as the controlling medium.

The type of valve[1] described in this note was designed, therefore, to use the pressure in the feed system between the valve and the injector as the opening impulse. For the simplest form of valve, this postulates that propellant is delivered at a relatively low rate until the passages between the valve and the injector have been filled, injection has taken place, ignition occurred and combustion been established, so that the sudden rise of pressure in the system downstream from the valve due to combustion causes the valve to open and deliver the full flow. This is a safe method of starting a rocket motor, as the initial rate of flow can be restricted to the minimum required for satisfactory initial combustion, and the full flow cannot be delivered until combustion is established.

2 Principle of operation

The main feature of this type of valve is the provision of a piston opposite to and connected with the valve head. The area of this piston is proportioned to almost compensate the closing force produced by the upstream pressure and thus enables the valve to be opened by the much lower pressure which acts on the entire downstream surface of the valve head. Fig.1(a) and 2(a) show diagrammatically how the closing force, produced by a relatively high pressure acting on the small uncompensated annular area plus a spring load, is balanced by a much lower pressure acting on the entire circular surface of the valve head. Fig.1 shows a starting valve in which the downstream pressure is predetermined by the flow through the annular pre-opening orifice and Fig.2 shows a second stage slow opening valve in which the downstream pressure is the chamber pressure developed by combustion of the initial starting flow of propellant acting back through the injector orifices. The calculations necessary for the design of these and similar valves are given in the appendix.

3 Applications and methods of operation

3.1 Rapid opening regulating valve for starting

Fig.1(b) shows a section through this valve, which is designed to feed through a pre-opening orifice of fixed size the initial flow of propellant for starting the motor. A burster disc upstream from the valve isolates the valve from the propellant tank until the latter is pressurized.

The sequence of operations is as follows:-

(1) The propellant tank is pressurized and causes the disc to burst.

(2) The passages between the valve and the injector are filled through the pre-opening orifice.

(3) The pressure rises in these passages, in accordance with the size of the pre-opening orifice, and propellant is injected into the combustion chamber at the initial starting rate.

(4) Ignition takes place in the combustion chamber in which the pressure rises in accordance with the rate of flow of propellants. This causes a further rise in pressure in the passages between the valve and the injector.

(5) The valve opens completely.

The valve can be arranged so that it opens at the end of stage 3, i.e. immediately the downstream pressure has been developed but it is usually more advisable and always safer to arrange for the valve to open at the end of stage 4, i.e. after ignition when the higher pressure has been developed in the passage between the valve and injector.

During the interval between the bursting of the disc and the movement of the valve to its fully open position a leakage path exists between the compensating piston and the cylindrical sleeve in which it moves. The leakage however, is very small as this time interval is of the order of one second only; it is, therefore, considered preferable to lead away the leaking fuel through the drain rather than attempt to reduce the leakage by making the compensating piston a close fit in the sleeve, with consequent increase of cost as well as risk of sticking. As can be seen, the piston when in the fully open position is held by the full feed pressure against a soft washer which gives a complete seal.

A valve of this type has undergone successful tests in which more than a hundred opening operations were carried out at different feed pressures. Opening always occurred instantaneously as soon as the pre-determined pressure downstream from the valve was reached. The seal in the fully open position was completely effective.

This valve and its associated burster disc has been designed for starting purposes only and it will be noticed that once the disc has burst the flow of propellant can no longer be shut off completely. It is, however, possible to reduce the flow again to the starting rate by connecting an impulse line from the upstream side of the valve through a solenoid vent valve to the drain connexion. In the full flow condition the solenoid valve is arranged to keep the impulse line closed and the drain open to atmosphere. When the solenoid is energized the pressure upstream from the valve is applied through the drain connexion to the lower face of the compensating piston. As the pressures on both sides of this piston are now equal the spring is able to return the valve head to its original position in which only the reduced flow takes place.

Such an arrangement also provides a means of selecting the instant when the valve opens. This is effected by applying upstream pressure through the energized solenoid valve and impulse line to the drain connexion whereby the valve cannot open until the solenoid is de-energized and the drain vented. In no case, however, can the valve open until the correct downstream pressure has been developed. It will be seen that with such an arrangement, a rocket motor could be run at two thrust stages, with reduced and full flow respectively, and with the possibility of selecting either at will.

3.2 Regulating valve for second stage

The valve shown in section in Fig.2(b) is designed to act as the second stage regulating valve for a rocket motor in which the first stage works at the full feed pressure and the propellant for operation of the second stage is fed through a separate injector system. The valve is arranged to seat completely in the closed position; as pressure due to combustion at the first stage develops in the passage between the combustion chamber and the valve, a force is built up to open the valve. The compensating piston is enclosed in a cylinder which is connected with the upstream side of the valve through a throttle orifice in order to reduce the rate of opening to the required value. The valve head carries a pintle of decreasing diameter which causes the area available for flow to increase steadily during the opening process. The sequence of operations is as follows:-

(1) When the propellant feed system is pressurized, pressure is applied to the valve head and through the throttle orifice to the compensating piston. The valve remains in the closed position until combustion has started and the combustion chamber pressure acts on the back of the valve head. The opening force is now large enough to overcome the closing force (see Appendix) and the valve starts to open.

(2) Until the valve is fully open, the upstream pressure is always higher than the downstream pressure and the valve head continues to be forced against the seat. Opening of the valve is effected by the opposing force of the upstream pressure acting on the compensating piston, and to maintain this force the liquid can only pass through the throttle hole at a low rate of flow which ensures that the valve opens slowly. The effect of the spring is to close the valve but only if the upstream pressure falls to a sufficiently low value.

(3) If the valve is to be shut at will, an impulse line controlled by a solenoid valve as described in para. 3.1 has to be fitted. This permits the valve to be closed at any time, but it can only be re-opened if the motor is running at the first stage so that pressure is available downstream from the valve.

(4) Usually the valve has to close as rapidly as possible. As the pressure above and below the compensating piston are equal, the spring load is the only force available to initiate the closing movement and the liquid above the piston must be allowed to escape from the cylinder as quickly as possible. This is effected by providing a flap washer which is clamped to the upper cover of the cylinder and which lifts in the centre to allow liquid to pass without much resistance through a wide clearance between the valve connecting pin and the central hole in the cover of the cylinder; holes in the

washer allow the liquid to escape. As soon, however, as the valve pintle is moved sufficiently to decrease the area available for flow throttling will take place, and the increasing difference between upstream and downstream pressures will increase the closing force at an increasing rate.

A valve similar to that shown in Fig.2(b) but designed for rapid opening has been tested and found to operate satisfactorily. It is now in use in a rocket motor in which it opens automatically a by-pass line to the second stage injector as soon as the combustion chamber pressure produced by the first stage propellant flow has been reached. Recordings have shown that the by-pass is fully effective at full flow 0.2 seconds after ignition following the first stage of injection.

3.3 Coupled regulating valves

Propellant regulating valves in rocket motors have not only to control the development of pressure at the injector, but also to ensure that the arrival of both propellants at the injector is either simultaneous or that a predetermined time interval, depending on the propellant combination, separates the arrival of one propellant from the other. In any case the pressure rise to full flow for both propellants should be simultaneous in order to ensure the correct mixture ratio at any instant. The required time of arrival of the propellants at the injector can be fixed by designing the respective burster discs to rupture at appropriate pressures and/or providing spaces of different volume downstream from the respective burster discs.

If the fuel and oxidant valves operate independently of each other it may be assumed that both will start to open at the same instant provided that they are set to open after ignition has taken place; this depends on the opening impulse reaching both valves simultaneously. If, on the other hand, the valves are set to be opened by the pressure rise caused by filling of the passages between the valves and the injector, they will open when the propellants arrive at the injector and there may be a period of time between the opening of one valve and that of the other depending on the propellant combination. If slow opening valves are used one may have a longer opening time than the other; this will result in an incorrect propellant mixture ratio during the opening process. It is, therefore, preferable to have the fuel valve mechanically linked to the oxidant valve. This is not a new idea, and it has been applied in rocket motors with good results. It has the effect of making the operation of the motor safer as neither valve can open if the other one sticks.

Fig.3 shows an arrangement of coupled fuel and oxidant starting valves, which operate as described in para. 3.1. Provision for slowing down the rate of opening need be made on one valve only, preferably on the larger one. It is, of course, essential that enough play be given to the pin joining the two valves to allow both pistons to seat properly on their respective washers in the fully open position.

A similar arrangement could be used for valves controlling the second or later stages of combustion, but the only reason for its use would be to prevent one valve operating if the other stuck. These valves would normally start to open simultaneously without being linked together because the combustion chamber pressure acts on both at the same moment. If the two valves are arranged to open slowly the effect of the difference in the opening times can be neglected because a slightly incorrect propellant mixture for a period of less than one second will not have serious consequences when stable first stage combustion has already been established.

4 Testing valves

It can be seen, as shown in the Appendix, that the pressure downstream from a valve needed to open it is a function of the pressure upstream from it. An initial test of a valve can be carried out at various propellant feed pressures. When, however, a complete motor is to be water-tested, propellant feed and combustion chamber pressures should be used which are similar to those obtained when the motor is fired so that the correct operating conditions for the valves are reproduced. To raise the combustion chamber pressure to the correct value during the water test, it is suggested that the modified form of throat blanking device shown in Fig.4 be used. The closing plate of the device incorporates a variable orifice, the area of which is controlled by a spring loaded piston. The proportions and size of the orifice can be calculated in accordance with the following procedure. First the combustion chamber pressures that would be obtained at different propellant flow rates when the motor is working must be estimated, and the respective flow rates corrected to allow for the fact that water is passing through the supply and injection system instead of propellant. At these chamber pressures the corresponding positions of the variable orifice valve piston can be determined, as the diameter of the piston and the rate of the controlling spring are both known. The area of the orifice at each pressure has then to be selected so that the pressure drop obtained is equal to the stipulated combustion chamber pressure for the corrected rate of flow of water out of the combustion chamber and through the valve. Finally the proportions of the orifice can be established.

This method of testing allows the operating conditions of the motor to be reproduced during the water test apart from the initial delay caused by the time taken to fill the combustion chamber volume with water. It is suggested that the procedure can be usefully applied to all water tests of this nature.

5 Application of the principle to other types of valve

The principle of operating a valve by the pressure downstream from it can be applied to liquid or air operated valves of normal type. Such a valve is shown in Fig.5. It will be seen that this valve has two concentric valve heads which are lifted by impulse pressure applied to a piston. The valve is kept closed by the spring load and the propellant supply pressure. The area of the operating piston is such that the impulse pressure applied to it is sufficient to lift only the smaller valve head. The area then opened to flow is sufficient to pass only the propellant flow required at starting. After, however, the pressure downstream from the valve reaches a predetermined value (see para. 3.1) the force acting below the external annular valve head added to that acting on the operating piston is sufficient to overcome the propellant supply pressure and hence the annular head lifts allowing the full propellant flow to pass. The valve can be closed at will by the removal of the operating pressure.

Valves incorporating a pilot valve, as used in the V.2 missile, can be made to work on the same principle. Fig.6 shows a valve of this type. Before the adoption of the new principle, the holes, shown in Fig.6, in the sleeve of the main valve were not provided. In this case when the propellant system is pressurized the pressure is allowed to develop above both valves through the passage formed by the small clearance between the sleeves of the cover and the main valve. When an impulse is applied to the operating piston the pilot valve is lifted and the pressure in the confined space is completely released; the pilot valve moves on to the spring ring and lifts the main valve.

To make this valve work on the new principle, an orifice has to be provided on the main valve sleeve, preferably by means of oppositely situated holes, as shown in Fig.6, to avoid lateral forces on the sleeve. As before, when a pressure impulse is applied to the operating piston the pilot valve is lifted, until it reaches the spring ring in the main valve and the initial starting flow is fed to the injector. The orifices through the sleeve of the main valve and the area of the pilot valve opening, however, are so proportioned as to maintain above the main valve a pressure which is high enough to prevent the valve from being lifted (see para. 3 of the Appendix) until the downstream pressure has reached a predetermined value which added to the pressure acting on the operating piston is sufficient to lift the main valve and allow the full propellant flow to pass. The valve can be closed at will by the removal of the operating pressure.

6 Conclusions

When a liquid is fed under pressure into an empty container or pipe system with a restricted outlet area a pressure is developed in the system at the instant when it is filled and ejection at the outlet starts. If this pressure is used to operate a valve which is to control the pressure in the system the following advantages are gained:-

(1) The initial pressure rise in the system and the initial rate of flow through it can be predetermined exactly.

(2) Further opening of the valve can take place only after this initial pressure has been reached.

(3) The operation of the valve is independent of the time needed to fill the system.

(4) The valve design is much simpler than that of other known valves serving similar purposes. Since the impulse opening the valve from partial to full flow acts within the valve directly on to the valve head, no special impulse line is needed for this purpose. The internal sealing components needed on the valve pin of a normal piston operated valve are unnecessary, and friction and the possibility of the valve sticking are much reduced. The size of the valve can be made smaller than that of a normal piston operated valve for the same flow.

REFERENCE

1 Covered by U.K. Patent Application No. 15520/51

Attached:

Drgs. R.P.613 - 618

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APPENDIX

Calculation of Valve Dimensions

1 Regulating valve for starting

This type of valve is shown in Fig.1. Assuming the full propellant flow is known, the main diameter of the valve is determined in the usual way. Likewise if the initial propellant flow for starting has been selected, the pressure drop through the injector at starting, Δp_i, can be calculated. The pressure developed downstream of the valve which is to be used for opening it can now be determined.

If the valve is required to open after the passages between injector and valve have been filled, the downstream pressure is

$$p_d = \Delta p_i \quad \text{lb/sq in}$$

If, however, ignition is to precede the valve opening to main flow the downstream pressure becomes

$$p_d = \Delta p_i + p_c \quad \text{lb/sq in}$$

where p_c is the combustion chamber pressure at the initial rate of flow of propellant.

The area A of the initially open orifice is calculated to deliver the initial rate of flow of propellant under a pressure drop of upstream pressure minus down stream pressure; that is

$$A = w/\left(2g\,(P_u - P_d)\,\rho\right)^{\frac{1}{2}} C_d \quad \text{sq ft}$$

where

w =	initial rate of flow of propellant	lb/sec
g =	acceleration due to gravity	ft/sec^2
P_u =	pressure upstream of valve	lb/sq ft
P_d =	pressure downstream of valve	lb/sq ft
ρ =	density of propellant	lb/cu ft
C_d =	coefficient of discharge of pre-opening orifice.	

In cases where the discharge coefficient of the initially open orifice C_d can be expected to be the same as that of the injector, the following simpler expression can be used, viz:

$$A = A_i \left(\Delta p_i/(p_u - p_d)\right)^{\frac{1}{2}} \text{sq ft}$$

where

A_i = total area of the injector orifice, sq ft

p_u = pressure upstream from valve, lb/sq in.

The diameter of the valve head, d_v can then be determined. The diameter of the compensating piston, d_p can be calculated from the following considerations:-

The valve head is in balance when

$$\frac{\pi}{4} \cdot d_v^2 \cdot p_d = \frac{\pi}{4} (d_v^2 - d_p^2) \, p_u + F_s$$

where

F_s = spring load when the valve is closed, lb

To ensure opening, however, the friction load of the valve, f lb has also to be overcome. As the dimensions of the spring are to be made large enough to overcome the friction, we have

$$f \leqslant F_s$$

and the equation for opening can be written with sufficient accuracy as

$$\frac{\pi}{4} \cdot d_v^2 \cdot p_d = \frac{\pi}{4} \cdot (d_v^2 - d_p^2) \, p_u + 2F_s$$

which gives the diameter of the compensating piston

$$d_p = \left[\left(\frac{\pi}{4} d_v^2 (p_u - p_d) + 2F_s \right) \frac{4}{\pi} \cdot \frac{1}{p_u} \right]^{\frac{1}{2}} \text{ in}$$

Finally, for any upstream pressure the corresponding downstream pressure at which the valve opens is

$$p_d = p_u \left(\frac{d_v^2 - d_p^2}{d_v^2} \right) + \frac{8F_s}{\pi d_v^2} \quad \text{lb/sq in}$$

2 Regulating valve

The calculations for this type of valve shown in Fig.2 are identical with those given in para. 1 above for the valve shown in Fig. 1. In this case, however, the opening force is the combustion chamber pressure produced by combustion of the initial flow of propellant through the separate first stage supply and injection.

3 Valve operated by impulse and downstream pressure

3.1 Type without pilot valve

This is the type of valve shown in Fig. 5. The calculations required are the same as those given in para. 1 of this appendix; in them the operating piston can be dealt with in exactly the same way as the compensating piston of a starting valve, provided that the impulse pressure and the upstream pressure are the same. Otherwise the equation for opening becomes

$$\frac{\pi}{4} d_v^2 \, p_d = \frac{\pi}{4} (d_v^2 \, p_u - d_o^2 \, p_o) + 2F_s$$

where

p_o = operating pressure lb/sq in

d_o = diameter of operating piston, in

and the diameter of the operating piston is then

$$d_o = \left[\left(\frac{\pi}{4} \cdot d_v^{\,2}\,(p_u - p_d) + 2F_s\right)\frac{4}{\pi} \cdot \frac{1}{p_o}\right]^{\frac{1}{2}} \text{ in}$$

3.2 Type with pilot valve

For this valve, shown in Fig.6, the pressure downstream has to be calculated as described in para. 1 of this appendix. The pressure, p_v lb/sq in. in the confined space above the main valve can then be selected, preferably equal to the mean value between p_u and p_d. The orifices in the sleeve of the main valve can then be estimated so as to deliver the initial rate of flow of propellant at a pressure drop across them of $p_u - p_v$ lb/sq in. The area of the pilot valve opening will be the same as that of the orifices in the sleeve of the main valve if

$$p_u - p_v = p_v - p_d$$

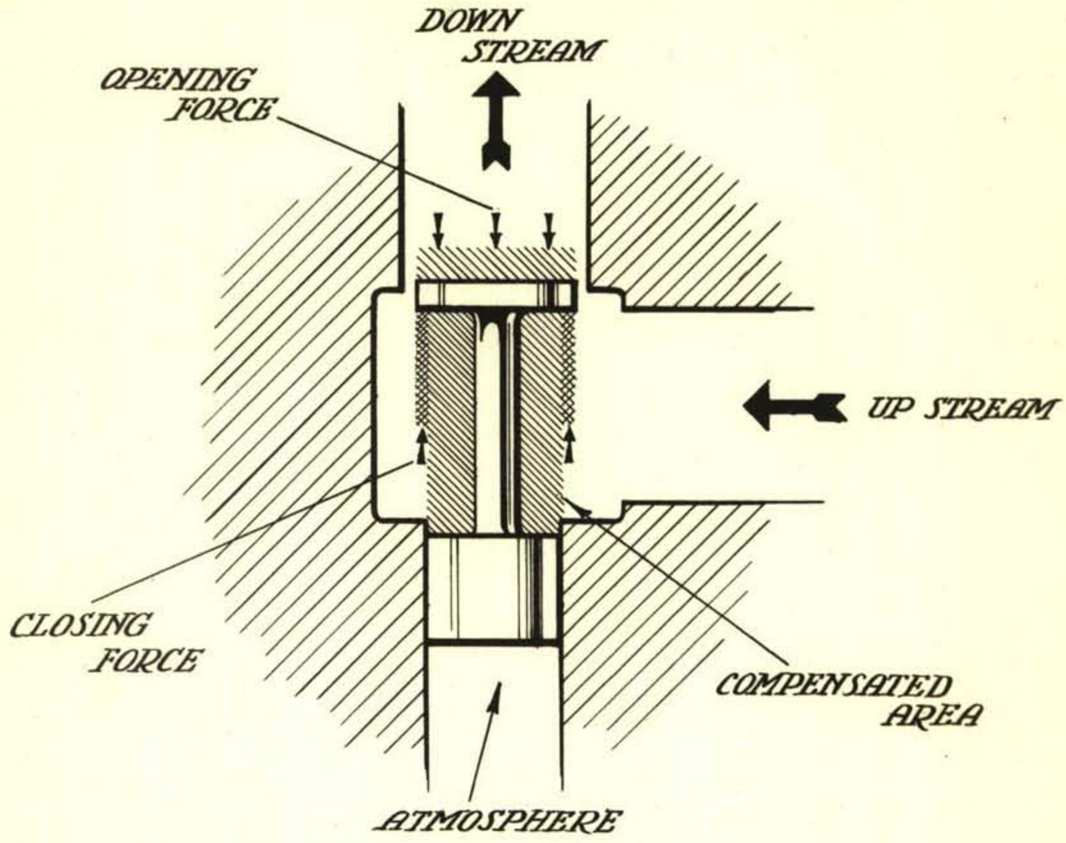
Provided that the diameter of the valve seat is the same as the diameter of the sleeve of the main valve so that p_u has no effect on the opening of the main valve, the equation for opening becomes

$$\frac{\pi}{4} \cdot d_o^{\,2} \cdot p_o + \frac{\pi}{4} \cdot d_v^{\,2} \cdot p_d = \frac{\pi}{4} \cdot d_v^{\,2} \cdot p_v + 2F_s$$

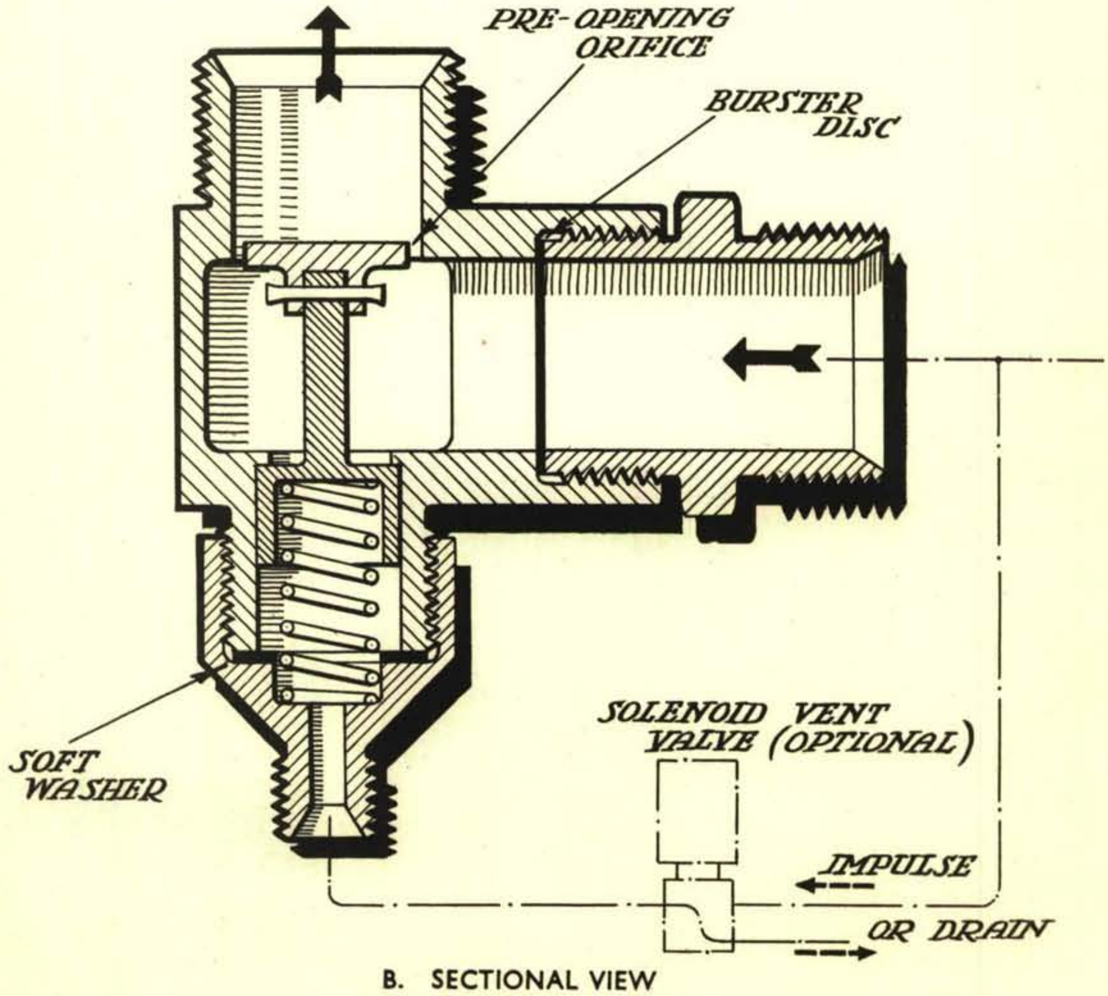
and the diameter of the operating piston is then

$$d_o = \left[\left(\frac{\pi}{4} \cdot d_v^{\,2}\,(p_v - p_d) + 2\,F_s\right)\frac{4}{\pi}\,\frac{1}{p_o}\right]^{\frac{1}{2}} \text{ in}$$

FIG. 1



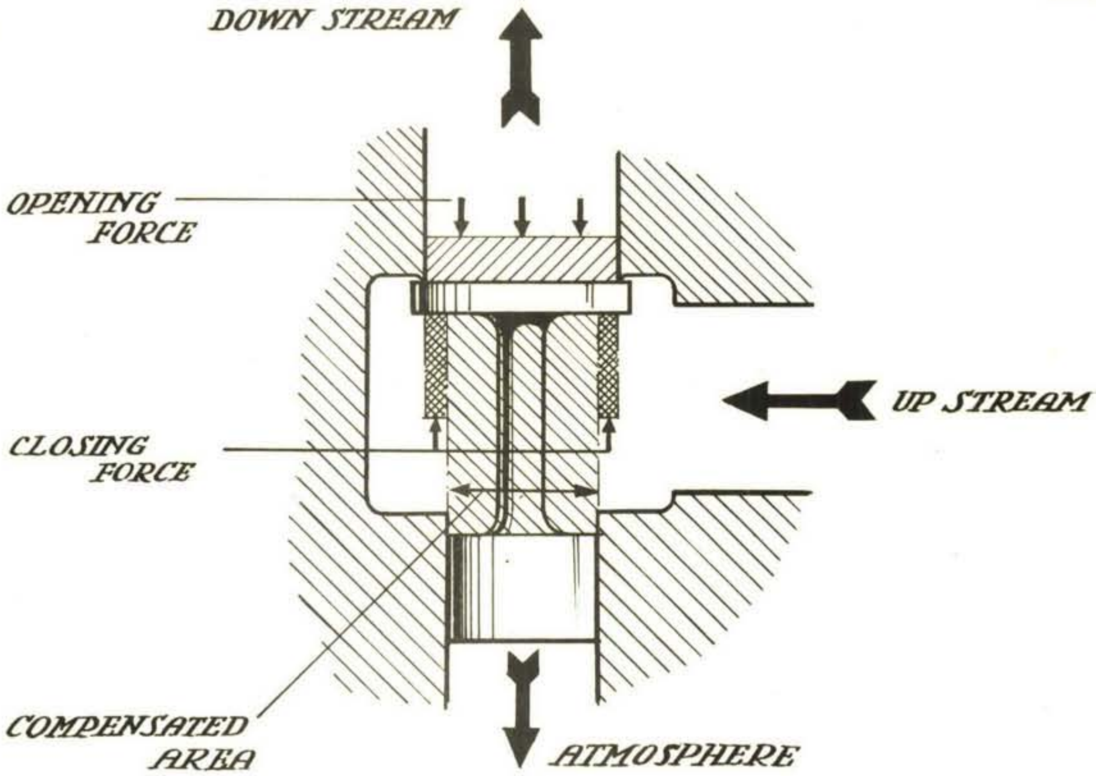
A. SCHEMATIC ARRANGEMENT



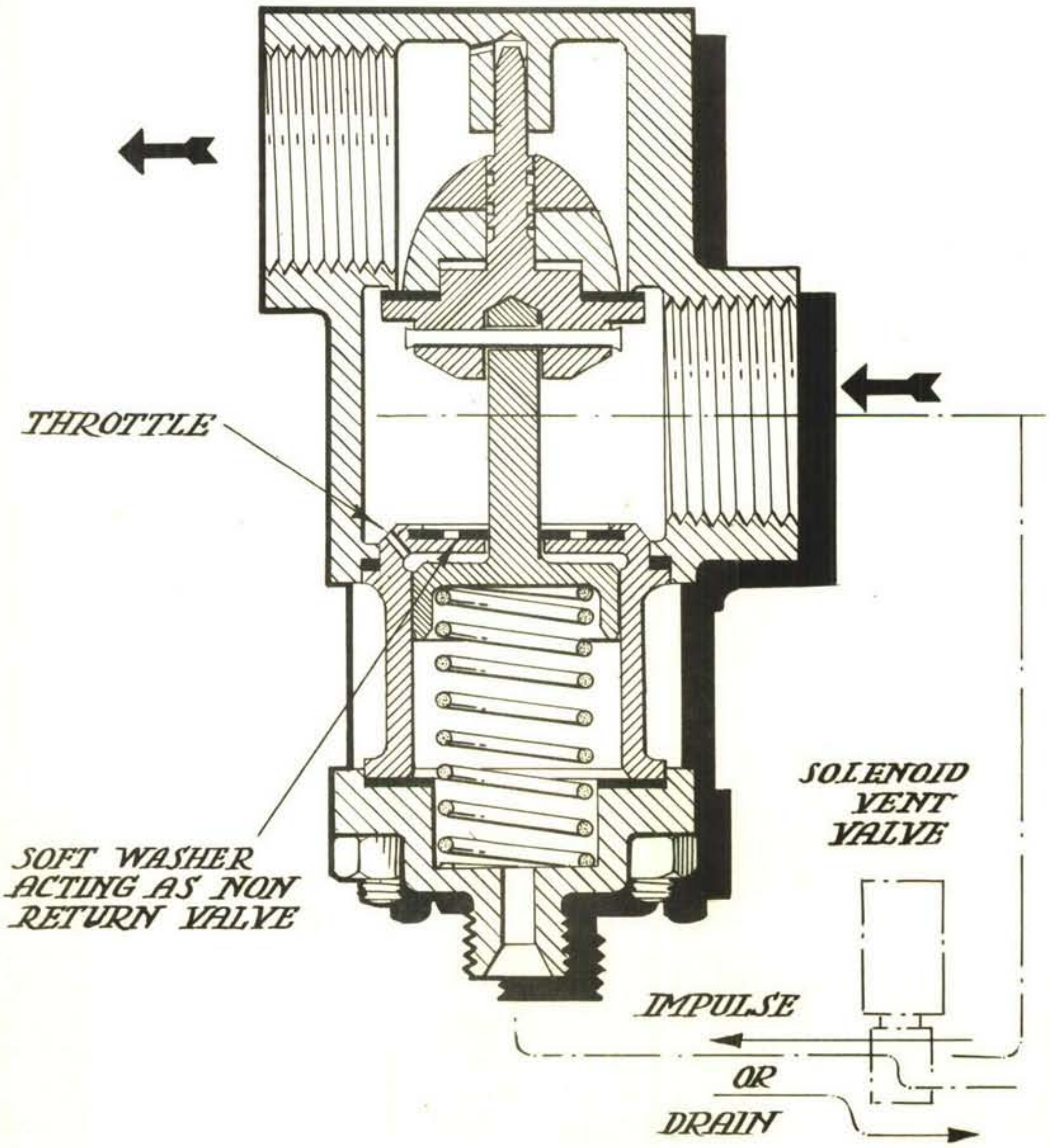
B. SECTIONAL VIEW

FIG.1. RAPID OPENING REGULATING VALVE FOR STARTING

FIG.2



A. SCHEMATIC ARRANGEMENT



B. SECTIONAL VIEW

FIG.2. REGULATING VALVE FOR SECOND STAGE

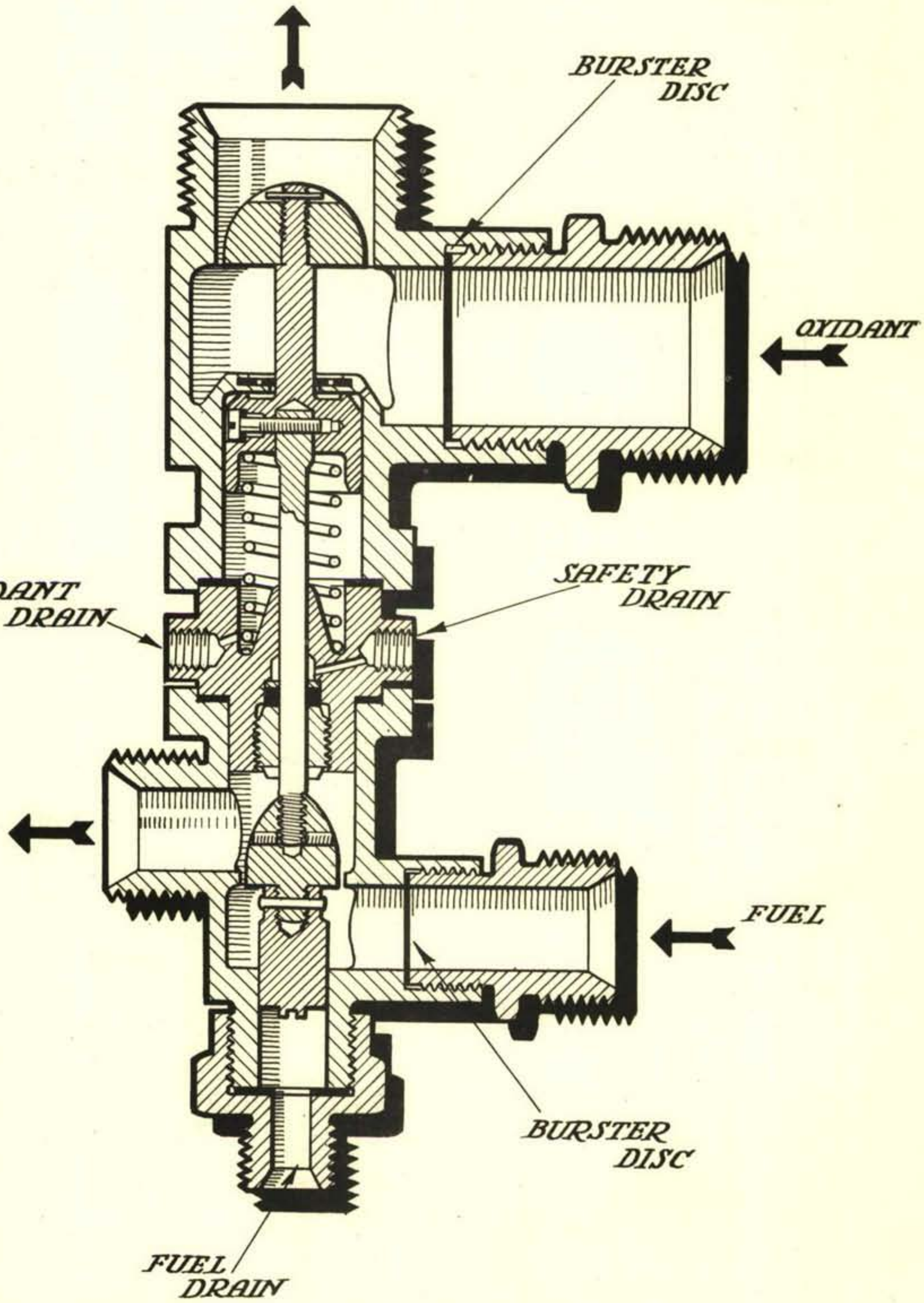


FIG.3. COUPLED REGULATING VALVES

FIG.4

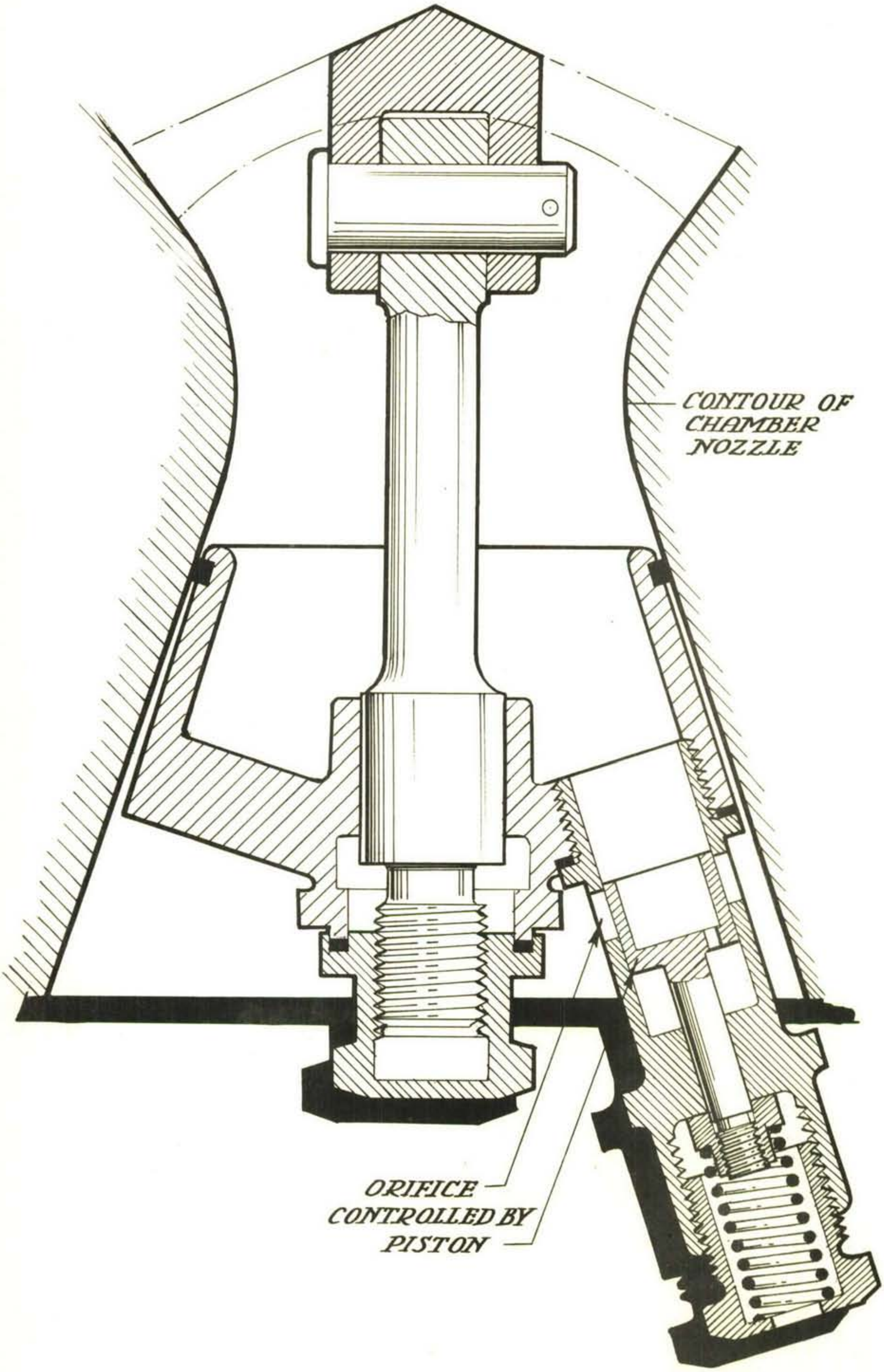


FIG.4. THROAT BLOCKING DEVICE WITH MEANS OF CONTROLLING CHAMBER PRESSURE DURING WATER TEST

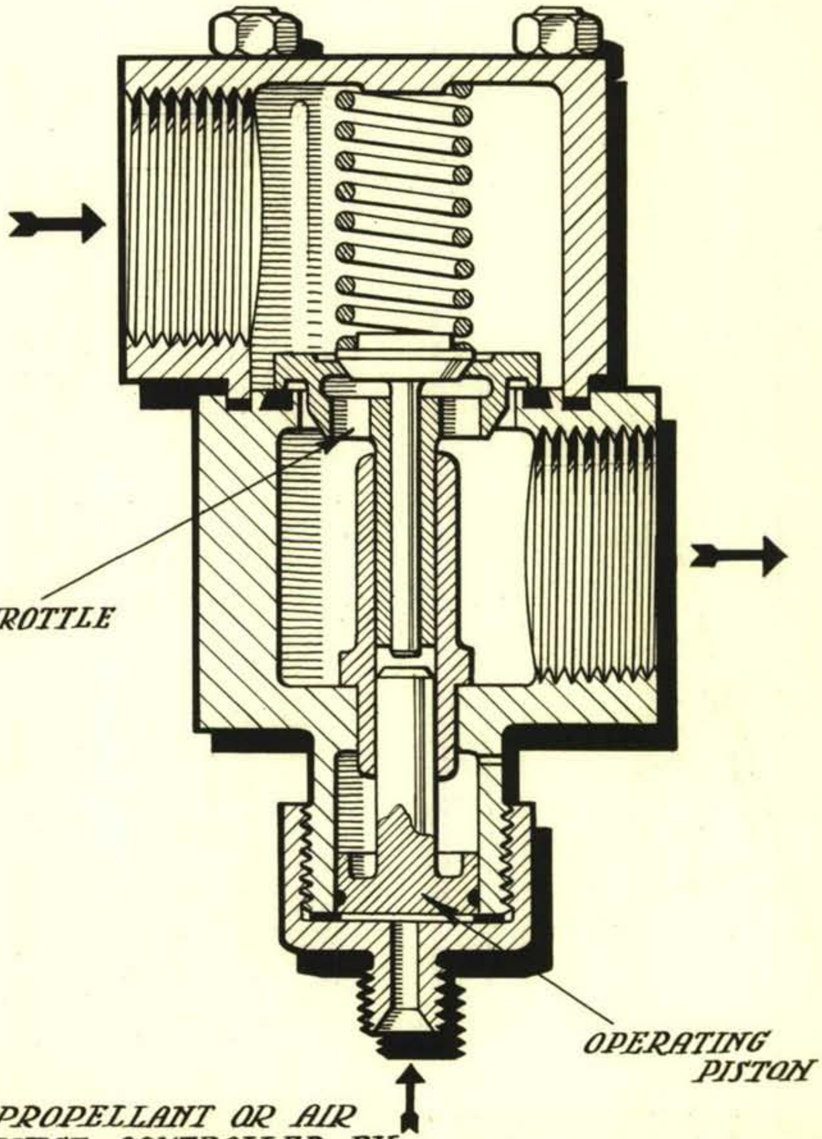


FIG.5. REGULATING VALVE OPERATED BY IMPULSE AND PRESSURE DOWNSTREAM

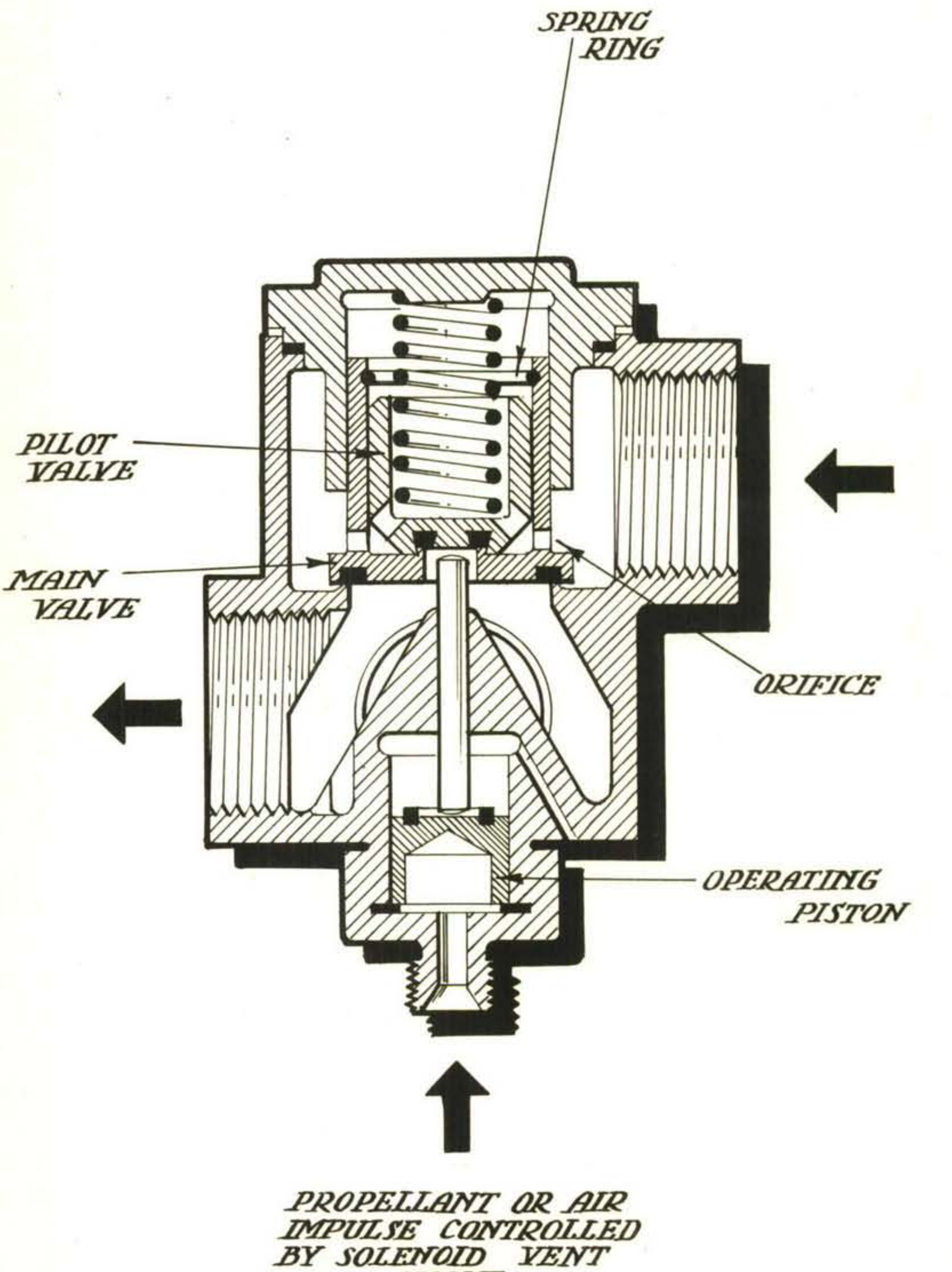


FIG.6. REGULATING VALVE WITH PILOT VALVE OPERATED BY IMPULSE AND PRESSURE DOWNSTREAM